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THESIS

**DEVELOPMENT OF AN ACOUSTIC STANDING WAVE
VESSEL FOR DIRECTIONALITY MEASUREMENTS**

by

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June 2023

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**DEVELOPMENT OF AN ACOUSTIC STANDING WAVE VESSEL
FOR DIRECTIONALITY MEASUREMENTS**

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ABSTRACT

The Sensor Research Lab (SRL) at NPS has been developing a biologically inspired microelectromechanical system (MEMS) sensor that is capable of determining the direction of an acoustic signal. This sensor has been well characterized in air, but not thoroughly tested in the underwater environment. NPS facilities are not suitable for properly characterizing the sensor's response over the intended frequency range, and partner facilities are expensive and logistically challenging to utilize. To shorten development cycle while decreasing costs, the SRL is developing a standing wave tube to serve as a testing environment for these sensors. The standing wave tube's acoustic properties were confirmed by comparing calibrated hydrophone measurements with the results of a finite element analysis carried out using COMSOL Multiphysics software. After characterizing the acoustic field inside the tube, sensor characterization measurements were taken in the standing wave tube and were compared to results measured in underwater facilities of partner Naval Warfare Centers. Analysis of measurements results indicated that comparable or better results could be achieved in the standing wave tube for a fraction of the water volume and cost.

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LIST OF ACRONYMS AND ABBREVIATIONS

BK 8103	Brüel and Kjaer 8103 Hydrophone
CAD	Computer Aided Design
DOA	Direction of Arrival
HP 467A	Hewlett-Packard 467A Power Amplifier
ILD	Inter-Aural Level Difference
ITD	Inter-Aural Time Difference
MEMS	Microelectromechanical System
MFLI	Mid-Frequency Lock In
PML	Perfectly Matched Layer
SOSUS	Sound Surveillance System
SR560	Stanford Research Systems SR560 Low Noise Pre-Amplifier
SRL	Sensor Research Lab
SWT	Standing Wave Tube
TRANSDEC	Transducer Evaluation Center

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I. INTRODUCTION

The harsh conditions of the undersea domain make its exploration and navigation exceptionally challenging. However, the pressure, darkness, and vastness that create such a challenging environment have also led to the development of a variety of sensing technologies; one of the most successful being sonar and other acoustic detection methods. The ability of sound to propagate long distances at a wide range of frequencies has made acoustic sensors critical to success in all aspects of underwater operations.

A. BACKGROUND

To aid in the detection and interpretation of acoustic signals, the Sensor Research Lab at the Naval Postgraduate School is developing an underwater micro-electro-mechanical system (MEMS) sensor based on the hearing organ of the *Ormia Orchacea* fly that is capable of very accurately determining the bearing of an acoustic signal. These sensors have reached the stage in their development where their acoustic response in water must be precisely characterized. One method of carrying out this testing involves the use of a water filled impedance tube, also known as a standing wave tube (SWT). This thesis will focus on the design, construction, and testing of a standing wave tube that can be used as an experimental environment for the characterization of the underwater acoustic MEMS sensor.

1. Modern Underwater Sensors

Modern acoustic sensors exist in a wide variety of types and configurations in order to serve a multitude of purposes. At the broadest level, sensors are either passive or active. Active sensors emit their own acoustic signal and then listen for the reflection to detect objects [1]. Meanwhile, passive sensors do not emit their own acoustic signal and merely listen to the environment [1]. The ability of both active and passive sensors to detect the direction of an incoming signal is greatly enhanced by employing a phased array. A phased array is uses multiple sensors are spatially arranged in a specific pattern so that each sensor registers the same acoustic signal at a different time [2]. Using this time difference, the speed of sound in water, and the physical separation distance between sensors, the array

can determine the direction the signal came from [2]. The phased array is the fundamental operating concept for many sonar systems that are widely used throughout the world. Two examples of this type of sonar system are the towed and spherical arrays. Both are highly effective systems that are capable of detecting acoustic signals and determining the source location from thousands of yards away [3]. The wide deployment of the towed and spherical arrays demonstrates how important acoustic sensors have become in all manner of maritime operations. Towed arrays have been deployed on surface ships, submarines, and aviation platforms for decades for both military and scientific applications [4]. Beyond the towed array, acoustic sensors have been used in weapons and underwater surveillance systems to great effect as seen in the MK-48 torpedo and Sound Surveillance System (SOSUS) [4].

Another type of acoustic sensor employed by the navy is the acoustic vector sensor. This type of sensor measures acoustic pressure and particle velocity simultaneously from one location [5]. Vector sensors often co-locate three orthogonal particle velocity sensors and a hydrophone to simultaneously record data the three-dimensional direction of particle motion and acoustic pressure at a location [5]. While this information alone can be used to estimate the direction of arrival (DOA) of an acoustic signal, digital signal processing techniques are usually applied to improve signal to noise ratio and enable a more accurate DOA estimation [1]. A multitude of methods exist, but two common approaches are beamforming and the histogram approach [5], [6]. The term beamforming has multiple meanings in regard to signal transmission and reception, but here it refers to a digital signal processing technique in which received signals are sorted based on direction [5]. This technique helps improve DOA estimation by removing noise from outside the direction of interest [5]. The histogram method is a statistical approach that counts the number of times that a signal arrived from a certain angle and designating the angle with the most occurrences the DOA [5], [6]. This method exploits the fact that noise is uniformly distributed across all angles of arrival while the signal of interest typically behaves as a normal distribution centered over the true DOA [6]. While they take different approaches, both methods significantly improve the accuracy of DOA determination by vector sensors. The accuracy and compact size of vector sensors relative to hydrophone arrays makes them

highly suitable for use in size restricted systems, like the United States' DIFAR sonobuoys [6].

2. Bio-inspired MEMS Sensor Based on *Ormia Orchacea*

The operating principles of the towed and spherical array sonar systems can be seen in nature across a wide variety of animals. The spatial separation of an animal's ears causes sound to reach them at different times, creating what is called the inter-aural time difference (ITD) [7]. ITD is the result of the sound reaching each ear at a different phase, which in turn creates a different pressure in each ear the inter-aural level difference (ILD) [7]. The animal then subconsciously processes the ITD and ILD and can determine the direction of the sound. However, the spatial separation can limit the frequencies that are able to be successfully detected; the separation distance must be relatively large compared to the wavelength of the sound otherwise the time ITD and ILD will not be large enough to accurately determine direction [7], [8]. There are some animals, like the *Ormia Orchacea* fly that have overcome this limitation and are able to determine the source of sounds with wavelengths much longer than the spatial separation between its ears [7]. The *Ormia* has tympanal membranes that are mechanically coupled which greatly amplifies the interaural differences [8], [9]. This mechanical connection causes sound to excite one of two possible bending modes depending on the location of the sound [8]. This quality is the motivation behind the development of MEMS sensors inspired by this insect. The sensors have two wings coupled by a bridge; these two pieces are constructed at precise dimensions so that incident sound waves excite a similar bending mode to what is found in the *Ormia Orchacea* [7], [10], [11]. The amount of bending experienced by the wing and bridge exhibits a cosine dependence with the angle of the incoming sound as in a gradient microphone [11].

3. Sensor Characterization Environments

The Bio-Inspired MEMS sensors being developed by NPS have been well characterized in air and have also been proven to be viable for underwater applications. Underwater, the accurate determination of the figures of performance such as sensitivity, frequency response, and directionality require specific experimental setups that emulate

the operation in open waters. The characterization of acoustic sensors involves carefully controlling the acoustic environment and extracting the pure sensor responses without the influence of the experimental conditions. In air this can be done by conducting experiments in an open field with low ambient noise or in an anechoic chamber that neutralizes nearly all reflections of sound. The aquatic analog would be the open ocean or an anechoic pool, respectively. Open ocean testing can be logistically and operationally challenging and might produce different results for a variety of unavoidable and uncontrollable factors such as surface conditions, water temperature, and salinity [12]. Additionally, depending on the experiment the noise produced by the carrier of the sensor, or the accurate placement of the sensor and source can also decrease the accuracy of the results [12]. The difficulties faced in the open ocean are mitigated in an anechoic pool, like the one at the Transducer Evaluation Center (TRANSDEC). The TRANSDEC pool has a 6-million-gallon volume and geometry that minimizes sound reflection and ambient noise [13]. TRANSDEC's pool recreates the open ocean environment but allows for more control over ambient conditions allowing for the precise characterization of sensors [13]. Replicating the qualities of the TRANSDEC anechoic pool on a smaller scale for in-house testing would significantly accelerate the development cycle. Smaller tanks are susceptible to large amounts of reflections that create a very complex acoustic field within the tank making it extremely difficult to accurately characterize the sensor's response at lower frequencies (100 Hz to 1 kHz) that are of interest in our case [13], [14]. A compact solution that minimizes reflections is a standing wave tube (SWT). A SWT is a cylindrical waveguide that allows for the one-dimensional propagation of acoustic waves with flat wave fronts [15]. This makes standing wave tubes ideal for a variety of acoustic applications like sound speed measurements, evaluation of reflection coefficients, and hydrophone calibration [15], [16].

B. THESIS ORGANIZATION

The goal of this thesis is the development and evaluation of a standing wave tube suitable for the characterization of direction-finding MEMS sensors in an underwater environment, at frequencies between 100 Hz and 1 kHz. The NPS SWT is intended to be used as the main experimental apparatus for characterization of future sensors. This evaluation will be made through computer simulations and measurements of the acoustic

field within the standing wave tube and comparison between measurements in the tube and measurements at the TRANSDEC anechoic pool. This thesis is organized into five chapters:

Chapter I provides context to the project by covering the need for underwater sensors, the basic principles of the *Ormia Orchacea* inspired sensor, and the different types of sensor characterization environments.

Chapter II covers the design of the standing wave tube. This section reviews previous applications of standing wave tubes and establishes the expected behavior of the SWT.

Chapter III explains how the acoustic profile of the standing wave tube was characterized.

Chapter IV describes the experimental set-up and procedures for the characterization of MEMS sensors in the standing wave tube. Additionally, data recorded in the standing wave tube is compared to data collected at TRANSDEC.

Chapter V discusses the implications of the results of this research and makes recommendations for future work.

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II. COMSOL SIMULATIONS

Before carrying out laboratory experiments, it is important to establish a baseline estimate of expected behavior. This is done in two ways, the first analyzes previous applications of standing wave tubes as acoustic testing environments and the second uses finite element analysis software to simulate physical phenomena on a computer model of the standing wave tube. Both methods provide an estimate of the magnitude and shape that is expected to be observed with the physical standing wave tube.

A. BACKGROUND

By looking at the physical equations governing the fundamental principles of the standing wave tube and the considerations made in historical uses of standing wave tubes, the short comings and the advantages of a SWT can be understood. This is important as it will help maximize the performance of the SRL's standing wave tube for sensor characterization.

1. Expected Behavior

The simplicity of the acoustic field within a SWT makes it a common choice for a variety of acoustic measurements. A standing wave tube is a cylindrical waveguide that, ideally, has an acoustic field composed entirely of waves with flat wave fronts when an acoustic source is placed at one end of the tube [15]. These flat wavefronts create a special waveform with the unique quality of having constant phase and amplitude along any plane perpendicular to the direction of propagation [17]. These waves are governed by the following equation

$$P = Ae^{i(\omega t - kx)},$$

where P is acoustic pressure, A is the amplitude of the source output, ω is the angular frequency, t is time, k is the wave number, and x is the distance from the source [17].

2. Previous Applications

Waves with a planar front are advantageous for acoustic testing because their homogeneity allows for control and experimental data to be recorded simultaneously, minimizing the impacts of the environmental conditions on testing results. For example, in 1981 Hetherington and Lombard used a water filled upright standing wave tube with a loudspeaker at one end to measure the neurological response of three different species of frogs to different sounds. They exploited the acoustic characteristics of the standing wave tube to simultaneously record the response signals from both hydrophones and frog's brain, ensuring the acoustic field recorded by the hydrophones was the same auditory signal stimulating the frog [18]. A similar study was conducted with African Lungfish in 2015 by Christensen, Christensen-Dalsgaard, and Madsen. Their study sought to study similar brain activity that Hetherington and Lombard were interested but in the African Lungfish [19]. In addition to simultaneous recording, both articles also cited the simplicity and lack of complex reflections as a reason for using a standing wave tube in their research [18], [19].

Traditional water tanks used for testing the underwater performance of equipment are undesirable for sensor characterization because they are susceptible to a large number of reflections that create a highly complex acoustic field [18], [19]. These testing environments can be useful for determining basic cause and effect but is undesirable for precise measurement of response due to specific signals, making them unfavorable for sensor characterization.

On the other hand, standing wave tubes can also be used as a testing environment for precision measurements like the calibration of hydrophones, reflection or transmission coefficient analysis, or impedance and sound velocity measurements [15], [20], [21]. For example, Wang, Thomas, and Wang used an impedance tube for the precise measurement of sound velocity in water [16]. Meanwhile, Wilson, Roy, and Carey focused on improving the construction of an impedance tube for the primary purpose of improved hydrophone calibration [15]. By using a tube with thicker walls and developing a non-obstructive hydrophone mount, they minimized disruption of the acoustic field within the tube [15]. Similar results were achieved by Lenhart, Sagers, and Wilson in their development of a standing wave apparatus specifically for the calibration of acoustic vector sensors [21].

With a sufficiently rigid wall and isolating acoustic source vibrations from the tube walls, they were able to achieve similar levels of calibration accuracy in the standing wave tube faster than in a free-field test [21].

3. Physical Construction

For this application the standing wave tube used was constructed using an aluminum tube with an inner diameter of 10 inches, a wall thickness of 1 inch, and a height of 24 inches. The tube was attached to middle of a 1 inch thick, 20"x20" aluminum plate with 6 ¼" mounting screw holes evenly spaced around the center of the plate. A computer aided design (CAD) drawing of the SWT is shown in Figure 1.

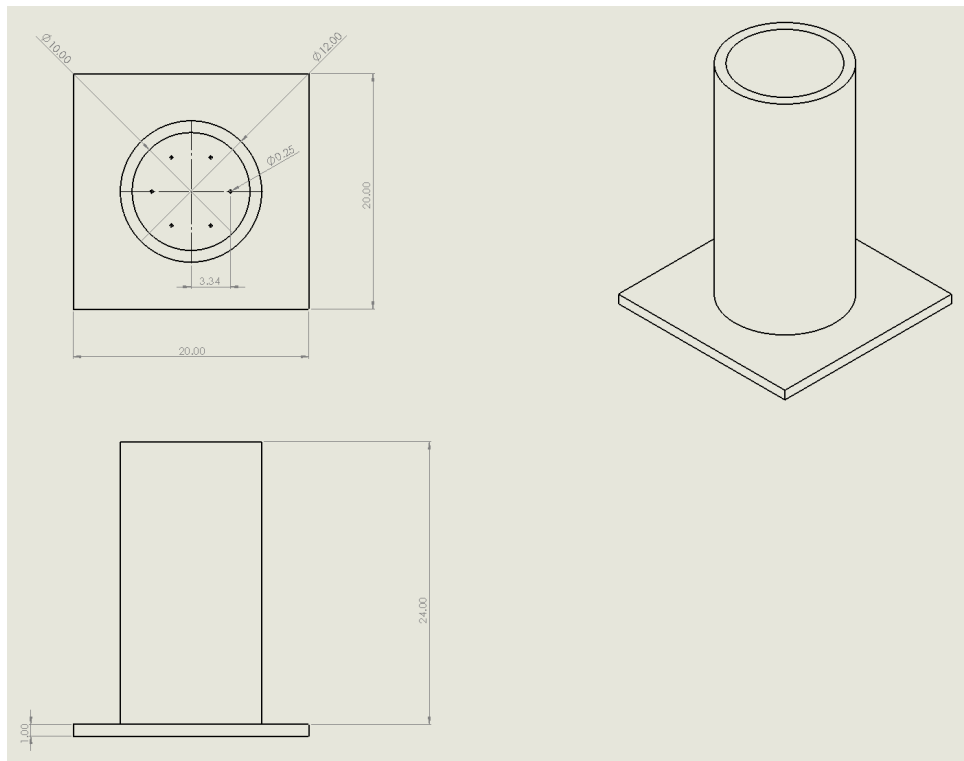


Figure 1. CAD Drawing of the Standing Wave Tube

In the upper left-hand corner of Figure 1 is a top view of the SWT is included to show the location of the mounting holes within the tube. The bottom left graphic is a side view, and the upper right is an isometric view of the standing wave tube. Additionally, the

SWT was given a poly-thiourea coating and painted white to prevent corrosion and improve visibility within the tube, respectively. Figure 2 shows the final assembly of the SWT.

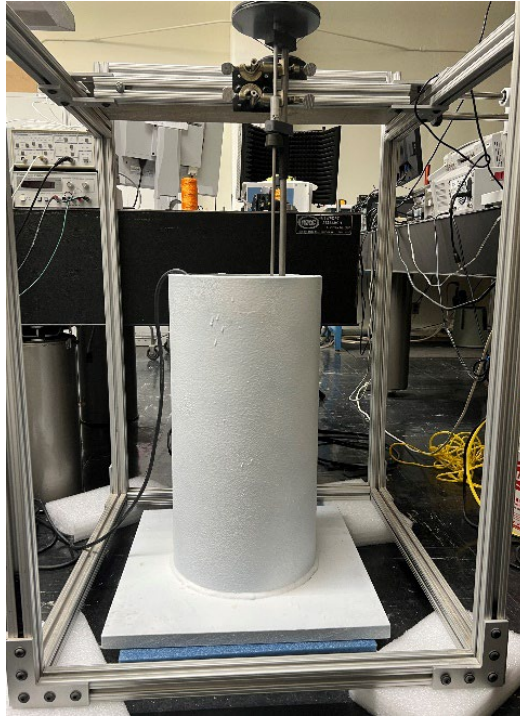


Figure 2. Standing Wave Tube Assembly

B. COMSOL SIMULATIONS

In order to establish a baseline of expected behavior of the SWT, a digital model of the SWT was created using COMSOL Multiphysics software. COMSOL is a finite element analysis software that is especially useful for simulating interactions between different physical phenomena [22]. This is important for the SWT model because the interactions between electromagnetism, acoustics, and structural physics will influence the acoustic field within the tube.

1. Geometry Definition

The tube was first reconstructed as symmetrical geometry. Similarly, a manufacturer provided model of the UW30 underwater loudspeaker used in the

experimental set-up was placed at the bottom of the tube. The model of the speaker was also cut in half and modeled as symmetrical geometry. The use of symmetrical geometry for the tube model was used in order to keep the model simple to minimize computation time. In addition to the tube structure and loudspeaker, a 1.5 ft water column was modeled within the tube and a perfectly matched layer (PML) at the top of the tube to replicate infinite space. Figure 3a shows the geometry used to define the structure of the SWT model and Figure 3b shows a diagram of the loudspeaker.

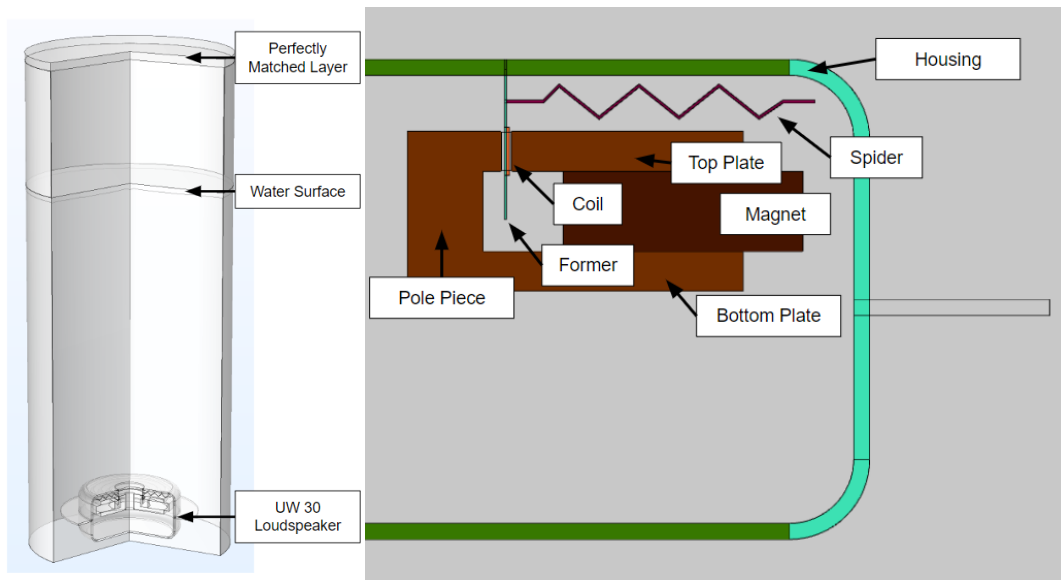


Figure 3. SWT COMSOL Model a) SWT Geometry b) Speaker Diagram

2. Input Parameters and Equations

Based off the model geometry, type of physics selected, and desired studies certain initial conditions must be provided before the simulation can be run. The first input parameters are for the initial conditions of the UW 30 loudspeaker. The loudspeaker in the model operates by taking an input voltage and known number of coils to output a range of frequencies at a volume that depends on these input parameters. For this model the number of turns in the loudspeaker coil was 100 and the peak driving voltage was 0.5 Volts. The other input parameters are critical to the accuracy of the acoustic studies of the COMSOL model. The first three are simple, maximum frequency, minimum wavelength, and sound

speed in air. Maximum frequency establishes the stopping point for acoustic studies, and minimum wavelength is the wavelength that corresponds to maximum frequency at the given sound speed. For all simulations the maximum frequency was 8 kHz, sound speed in air was 343 m/s, and therefore minimum wavelength was 42.9 mm. Final parameters are related to the eigenfrequency analysis that the model will complete. They are the frequency at which loss factor is given and angular frequency at which loss factor is given. The frequency at which this loss factor is given is set at 40 Hz, and therefore the corresponding angular frequency is 251 rad/s. These values are used to calculate loss factor for certain materials in the UW 30 speaker model. The manufacturer's model uses the angular frequency along with other material properties to calculate loss coefficients for certain components within the speaker. The inclusion of loss factors in the model is a method of accounting for damping effects within the simulation [23].

The COMSOL model solves a few fundamental equations to run the simulation and determine the quantities of interest. The first two equations are from the Lorentz Coupling portion of the multiphysics section of the model. The Lorentz Coupling allows for magnetic field effects to be translated into solid mechanics effects [24]. First, the electrical current density, J , is calculated with the following equation:

$$J = \sigma(E + v \times B)$$

where σ is conductivity, E is the induced electric field, v is the velocity of the moving coil, and B is the magnetic flux density [24]. Then the electric current density is used to calculate the Lorentz Force, F , by using the following equation provided by [25]:

$$F = J \times B .$$

Another important set of equations comes from the acoustic-structure coupling. This allows for the simulation to account for the effects of pressure acoustics on structural components [25]. The first equation establishes a boundary condition at the interface of the acoustic field and the structural element. The boundary condition established by [25] is

$$-n \left(\frac{-1}{\rho_c} (\nabla p_t - q_d) \right) = -n \cdot u_u ,$$

where n is the surface normal, p_t is total acoustic pressure, ρ_c is complex density, and q_d is the dipole domain source. The final equation provided by [25] represents the actual force per unit area, F_A , on the structure itself:

$$F_a = p_t n .$$

3. Deformation Testing

With the standing wave tube replicated as COMSOL geometry and established input parameters, the simulation was run to obtain three main outputs of interest: structural deformation, eigenfrequency, and sound pressure level. Structural deformation is the amount deflection experienced by different physical components of the model. Deformation within the speaker is both expected and acceptable as it is what creates the acoustic field. However, deformation of the tube wall will disrupt the acoustic field by disturbing the flat wave front. Figure 4 shows the deformation of the model at 450 and 630 Hz. These two frequencies are selected because they are near the resonant frequency of the MEMS sensors that will be primarily tested in this standing wave tube.

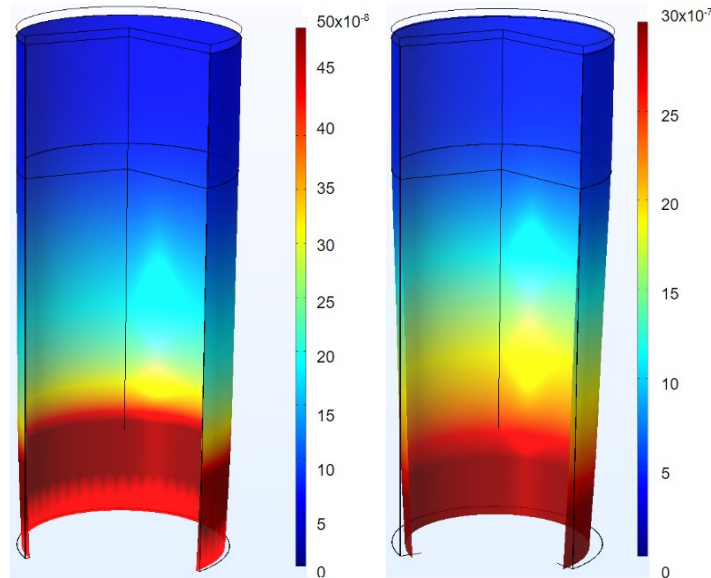


Figure 4. Structural Deformation of a) 450 Hz and b) 630 Hz

Figure 4 seems to suggest a large amount of deflection in the walls of the standing wave tube; however, the scale is on the order of 10^{-8} and 10^{-7} meters for 450 and 630 Hz, respectively. Additionally, the deflection observed near the base of the walls of the standing wave tube is only perceivable because it has been scaled up by 150 times. This amount of deflection is negligible when compared to the wavelength of the sound waves.

4. Eigenfrequency Analysis

Another important study carried out with the COMSOL model was the eigenfrequency analysis. This study produced a table of the eigenfrequencies, or natural frequencies, that exist in the standing wave tube. At these specific frequencies, there will be strong fluctuations of the acoustic pressure over the tube's length due to the formation of nodes and antinodes [17]. This non-uniform acoustic field is problematic for sensor characterization as it can create ambiguity about if the sensor's response is caused by a defect in sensor design or abnormalities within the acoustic field. For that reason, the eigenfrequencies of the standing wave tube should be well outside the range of interest. Table 1 summarizes the first 10 eigenfrequencies determined by the COMSOL model.

Table 1. COMSOL Model Eigenfrequencies

Eigenfrequency (Hz)
$279.0 + 380i$
$411.6 + 63i$
$445.29 + 51i$
$1771.0 + 121i$
$1939.3 + 129i$
$3782.2 + 188i$
$3951.4 + 213i$
3972.2
5563.5
5755.3

The operating range of the sensors that are intended to be tested in the standing wave tube is roughly 200 Hz to 1.5 kHz, so any value above 2 kHz is acceptable as it is sufficiently far from the range of testing frequencies. Additionally, the imaginary portion

of a complex eigenfrequency represents the temporal absorption coefficient, β , a measure of how quickly oscillations at that frequency dissipate in the system [17]. Large values of β , as observed in the eigenfrequency study, correlate to a small amount of time for vibrations to damp out of the system, meaning that these modes will not persist within in the standing wave tube for a long enough to impact sensor characterization [17].

5. Sound Pressure Level

The sound pressure level study provides the acoustic pressure throughout the tube at a given frequency. This study visualizes the shape of the acoustic field and indicates whether a flat wave front is propagating within the standing wave tube. Figure 5 shows the sound pressure level graphic generated by COMSOL for both 450 Hz and 630Hz. The contour lines on the graphic give a clear indication of the different pressure level boundaries, which represent wavefronts.

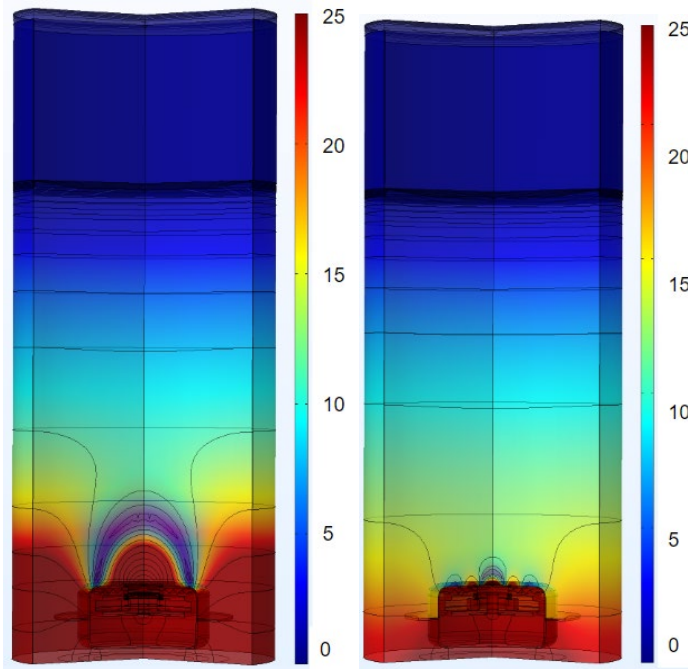


Figure 5. Sound Pressure Level within SWT at a) 450 Hz and b) 630 Hz

Near the loudspeaker, there are regions of the acoustic field that are non-planar; however, below the water-air boundary to the middle region of the tube the contours of the

pressure level are planar, which still provides a large region of flat wavefront, suitable for sensor characterization. Together, these three simulation results provide a baseline for the expected behavior of the standing wave tube.

III. STANDING WAVE TUBE CHARACTERIZATION

While the COMSOL model predicts that the acoustic profile of the standing wave tube is suitable for sensor characterization, the physical profile must be verified. To characterize the acoustic behavior of the standing wave tube two experiments were carried out: the linear field test and flat wavefront test.

A. EXPERIMENTAL SET-UP

The acoustic source for experiments within the standing wave tube was a UW 30 underwater loudspeaker driven by a Hewlett Packard 467A (HP467A) power amplifier. In order to minimize the number of vibrations that are transferred from the loudspeaker to the walls of the standing wave tube, the loudspeaker was placed on fully inflated 2.80/2.50-4 tire innertube. The innertube was attached to the bottom of the standing wave tube by using cable ties to secure it to four screws placed in the quarter inch mounting points at the bottom of the standing wave tube. Figure 6 shows how the inner tube was attached to standing wave tube and the final assembly with both the innertube and loudspeaker in place.



Figure 6. SWT Acoustic Source a) Innertube Dampener and b) Loudspeaker

A Brüel and Kjaer 8103 (BK 8103) hydrophone with calibrated sensitivity of $23.6 \mu\text{V}/\text{Pa}$ ($-212.6 \text{ db re } 1 \mu\text{V}/\text{Pa}$) in the frequency interval between 10 Hz and 1 kHz was used for measuring the acoustic field within the standing wave tube and a Stanford Research Systems SR560 Low-Noise Preamplifier (SR560) was used to apply gain to the hydrophone's signal [26]. To control the system both the HP467A and the SR560 were connected to a Zurich mid-frequency-lock-in (MFLI) amplifier that is controlled by a computer. Figure 7 is a block diagram of the experimental setup and Figure 8 shows the connected equipment as used in the laboratory.

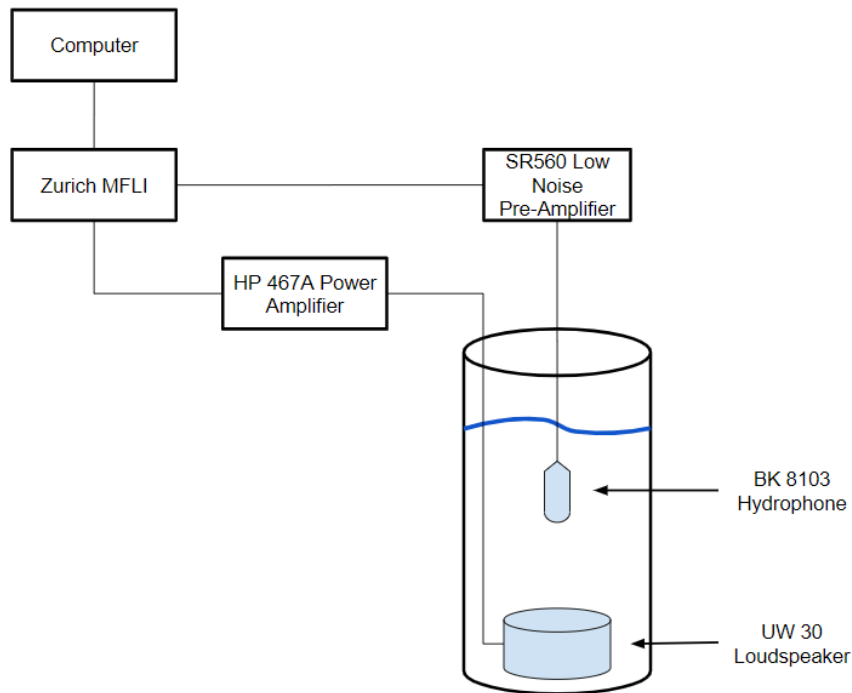


Figure 7. Block Diagram of Experimental Equipment

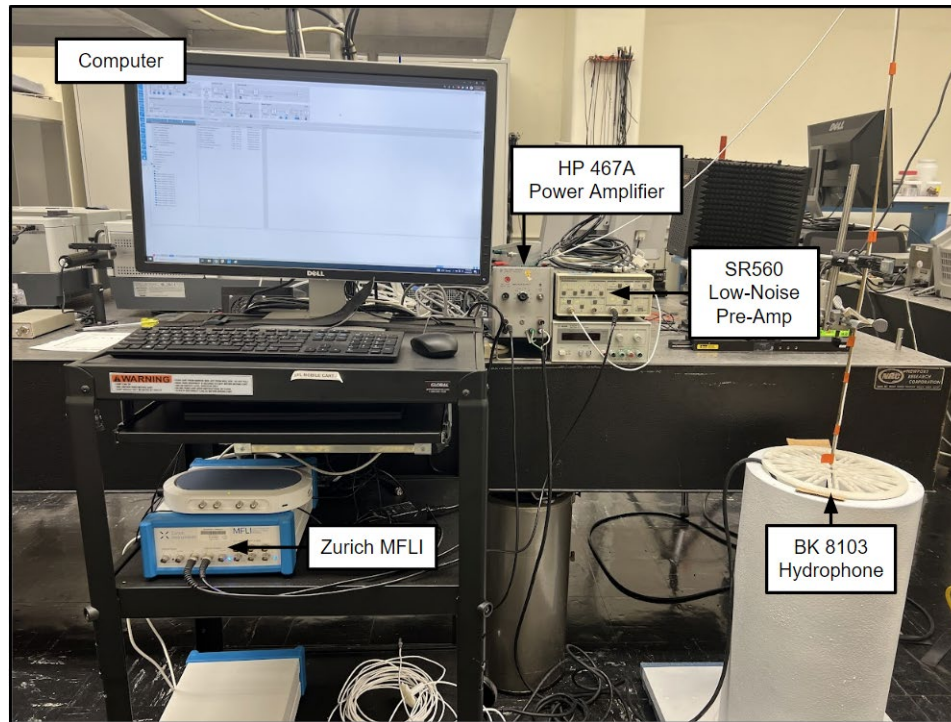


Figure 8. Standing Wave Tube Characterization Experimental Setup

B. LINEAR FIELD TESTING

To verify that the acoustic profile of the standing wave tube is suitable for sensor characterization, the acoustic pressure at fixed depth and varied frequency was measured when the output driving voltage from the Zurich MFLI set at 10 and 100 mV. The output voltage from the Zurich MFLI was given a seven times amplification by the HP 467A therefore, the peak input voltage to the loudspeaker was 70 and 700 mV. The purpose of this test is to see how frequency influences acoustic pressure within the tube and to verify that acoustic pressure linearly varies with loudspeaker excitation voltage.

This test was carried out in the center of the standing wave tube at 3, 6, and 9 inches below the surface of the water column. The output frequency of the loudspeaker was swept from 200–1000 Hz in 10 Hz increments. The voltage response of BK 8103 was amplified 100 times by the SR560 before being recorded in millivolts. The voltage response, R , was converted to acoustic pressure, P , by dividing it by the amount of gain applied to the signal, G , and the sensitivity S . This is demonstrated in the following equation.

$$P = \frac{R}{S \times G}$$

Figures 9–11 show the acoustic calculated for each depth and both 10 and 100 mV of driving voltage.

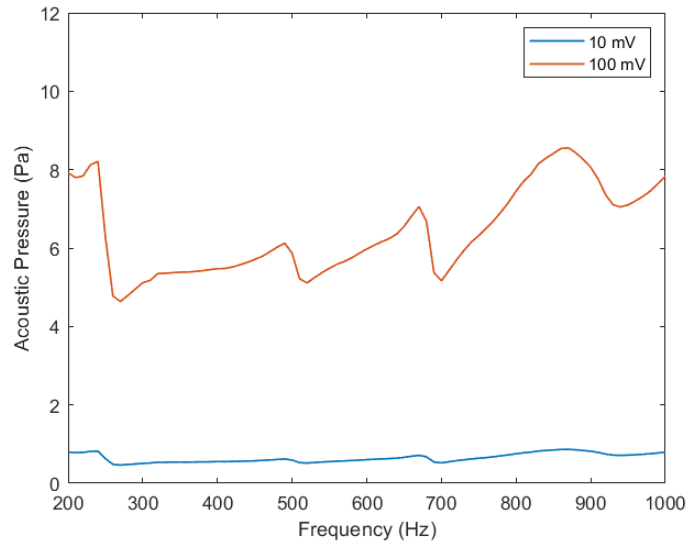


Figure 9. Acoustic Pressure at 3-in Depth

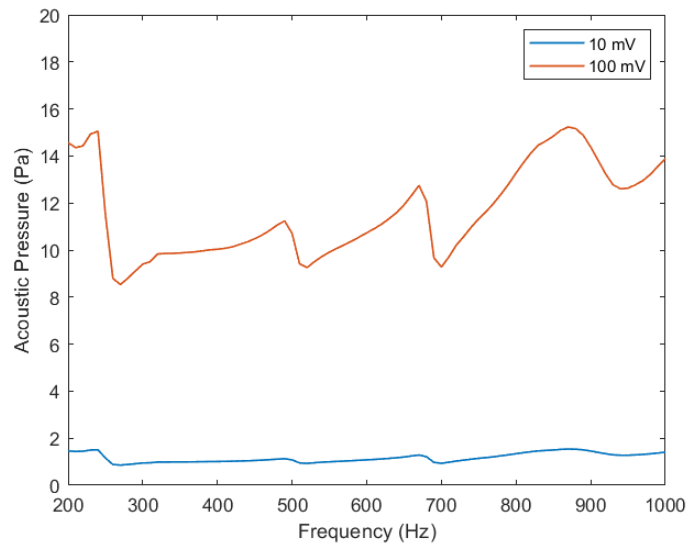


Figure 10. Acoustic Pressure at 6-in Depth

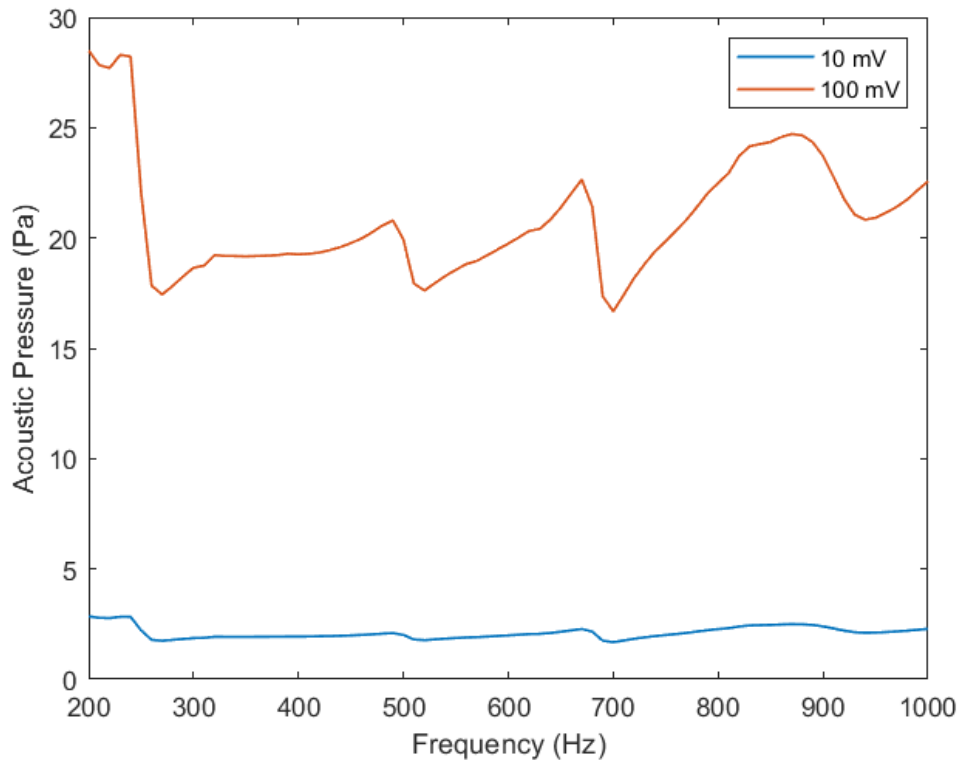


Figure 11. Acoustic Pressure at 9-in Depth

To ensure that the acoustic field linearly varies with driving voltage, the pressure calculated from the 100 mV was divided by 10 mV. The acoustic field in the standing wave tube behaved as expected as the 10-mV pressure was 10 times less than what was measured at 100 mV. Figures 12–14 show that over the frequency range the pressure ratio is very nearly 10 for all frequencies. Across all measurements the maximum difference between the calculated ratio and the expected value was less than 1%, indicating that acoustic pressure does vary linearly with driving voltage at a fixed depth.

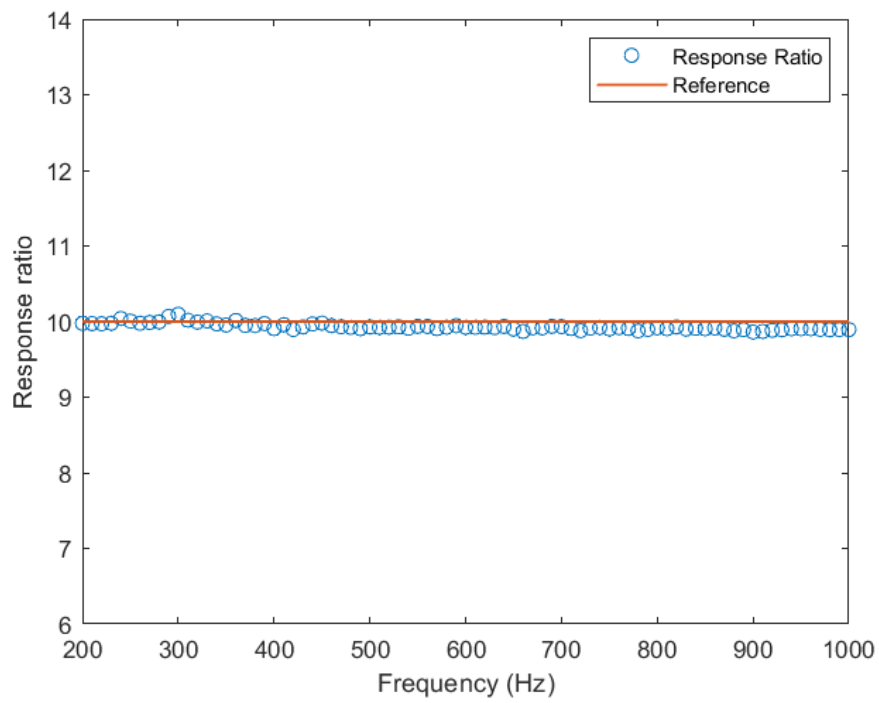


Figure 12. Pressure Ratio at 3-in Depth

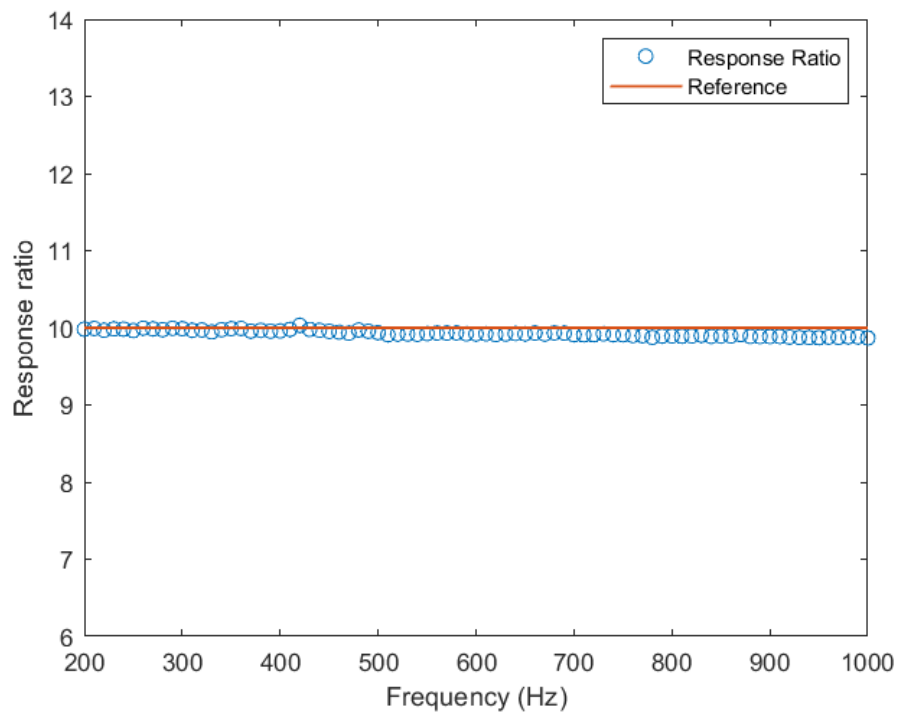


Figure 13. Pressure Ratio at 6-in Depth

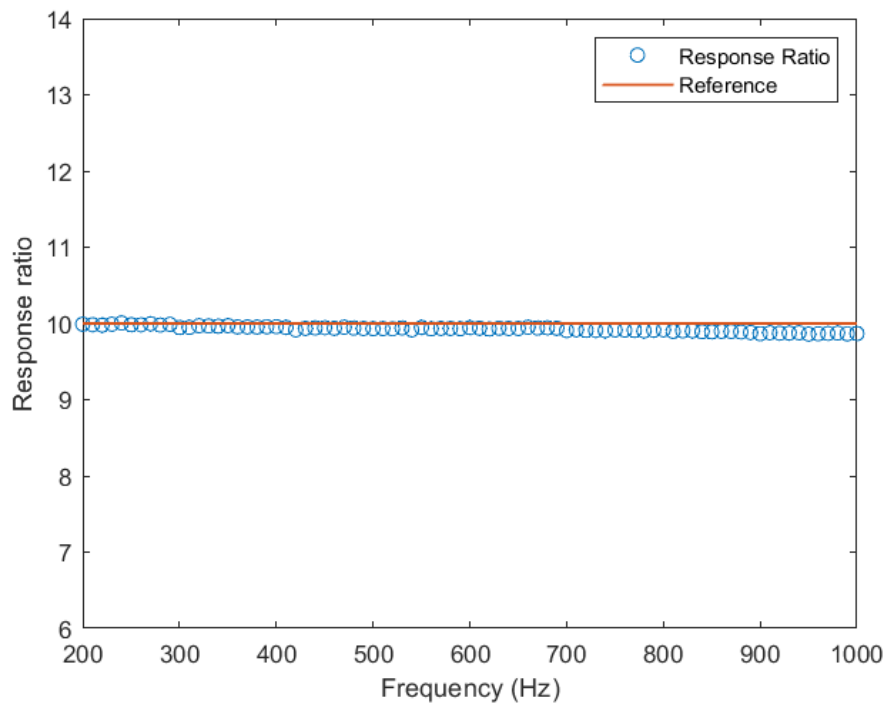


Figure 14. Pressure Ratio at 9-in Depth

C. FLAT WAVEFRONT TESTING

To establish the physical acoustic profile of the standing wave tube, 3 fixed-depth cross sections, each composed of 69 different points, were measured. At a fixed depth, by measuring the hydrophone voltage response and converting it to sound pressure using equation 2 for each location, the shape of the acoustic field can be determined. The measurement points were selected by placing a 1 inch by 1 inch grid centered over the standing wave tube and removing all points on or outside of the tube wall. Figure 15 is a sketch that illustrates the points where measurements were taken at each depth. The tube wall is represented by the cross hatched ring, the measurement locations are the points within the ring, and the center is marked by an x.

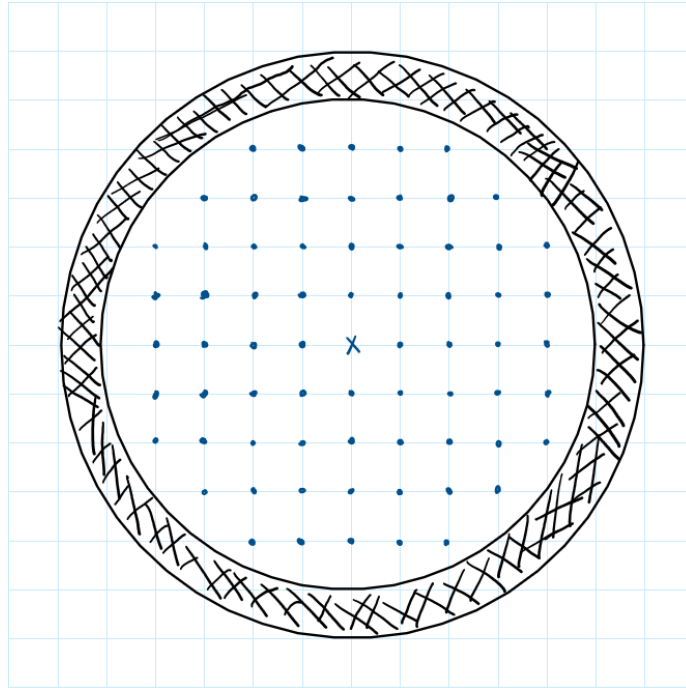


Figure 15. Location of Cross-Sectional Measurements.

To accurately place the hydrophone at each location, an apparatus using optical breadboard equipment was constructed. The apparatus consists of an arm with two clamps at the end attached to a slider mounted on an optical table. The surface of the optical table is a uniform 1 inch by 1 inch grid, giving each point a corresponding location within the standing wave tube. To align the optical table grid with the desired standing wave tube grid, a 3D printed cross section of the tube was used. The cross section shown in Figure 16 fits exactly within the inner diameter of the SWT and has a hole marking the center of the SWT. While the apparatus was at the center location on the optical table, a rod holding the BK 8103 was placed in the clamps and the SWT was moved into position so that the rod went directly through the center of the cross section as shown in Figure 17.

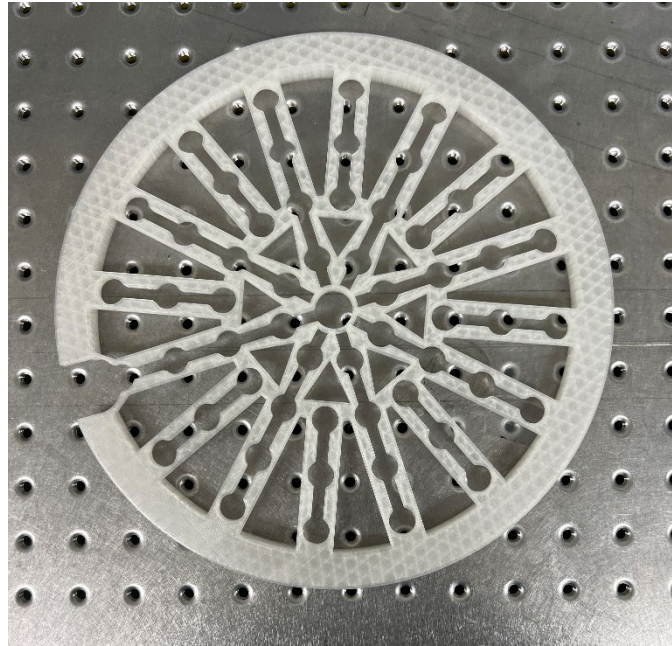


Figure 16. 3D Printed Cross Section

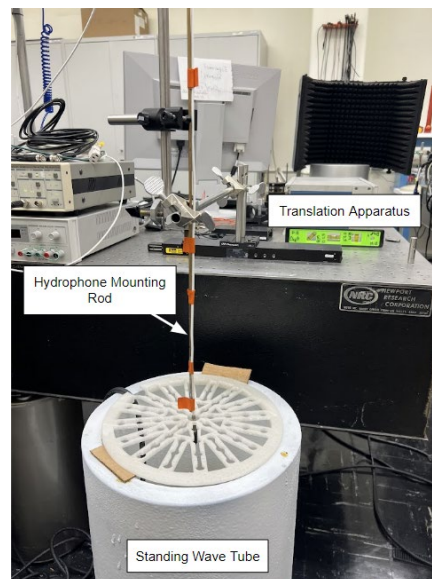


Figure 17. Alignment of SWT with Measurement Apparatus

After the SWT was aligned with the optical table, it was not moved and only the apparatus on the optical table was moved to each location. Using the slider, the apparatus was moved across an entire row of measurement points, after measuring at the final point

of the row, the apparatus was removed from the table and reattached on the next row so the process could be repeated.

At each point the measurements consisted of driving the loudspeaker with 500 mV of power over a 200–1000 Hz frequency range and measuring the voltage response of the B&K 8103 hydrophone after being amplified by a factor of 100 by the SR560 at each of the 69 points. Cross sections were measured at 3, 6, and 9 inches below the surface of the water. The water column was 18 inches measured from the bottom of the SWT to the surface, but because the speaker is on top of the innertube, the distance between the surface of the speaker to the surface of the water is 13 inches. Figures 18–20 show a surface plot of acoustic pressure at a given location at the cross section within the tube. The blue ring shown in the surface plots is a reference mark that represents the standing wave tube wall.

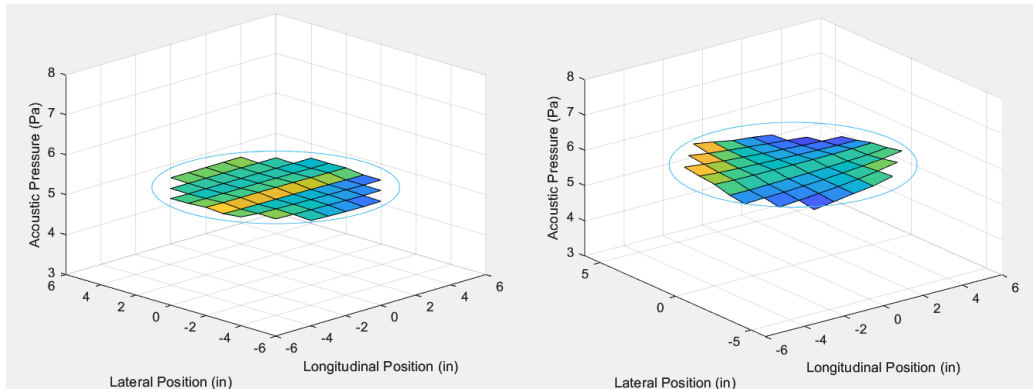


Figure 18. Acoustic Pressure at 3-in Depth at a) 450 Hz and b) 640 Hz

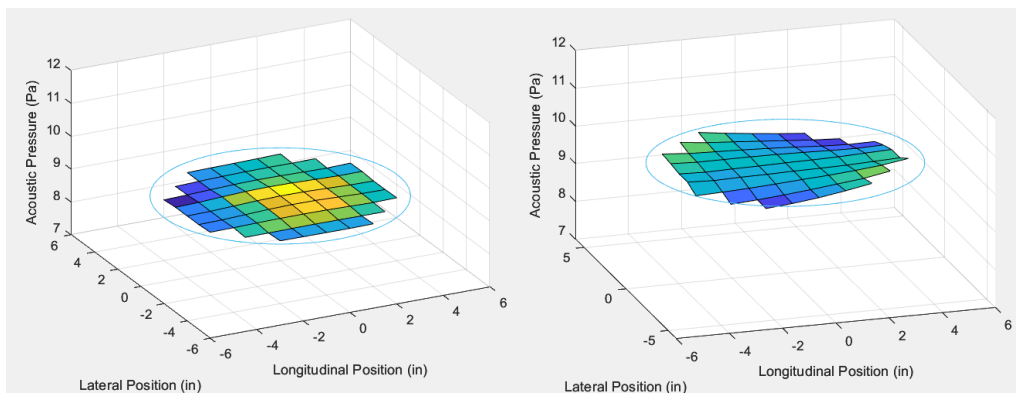


Figure 19. Acoustic Pressure at 6-in Depth at a) 450 Hz and b) 640 Hz

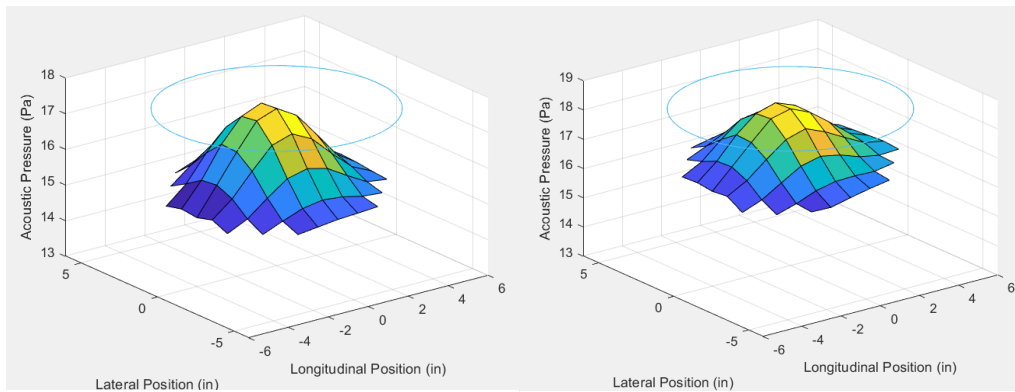


Figure 20. Acoustic Pressure at 9-in Depth at a) 450 Hz and b) 640 Hz

The results from the flat wavefront testing matched what was predicted by the COMSOL model; the standing wave tube has a large volume with flat wavefront propagation at both 450 and 640 Hz. The 450 Hz tests for both the 3- and 6-inch depths show two flat cross sections with an average acoustic pressure of 5.15 Pa and 8.92 Pa respectively. The standard deviation of both is 0.026 Pa. The 3-inch depth 640 Hz plot has an average acoustic pressure of 5.83 Pa and the 6-inch depth plot has an average of 9.90 Pa. Both 640 Hz plots have a few deviations near the edges of the surface plot, this is exemplified with both depths having a standard deviation of 0.1 Pa, nearly four times larger than what is observed in the 450 Hz plots. The larger standard deviation likely stems from the proximity of the hydrophone to the tube walls. The outermost measurement points were at most 1 inch away from the tube's walls with many of the corner points being much less than an inch from the walls. At this distance the hydrophone is susceptible to any additional acoustic pressure that may be generated by vibrations in the tube walls, even if very minor. At the 9-inch depth, there is not a flat wavefront. This agrees with the COMSOL simulations since a 9-inch depth places the hydrophone only 4 inches away from the loudspeaker in a region where a flat wavefront is not expected to form. Since the region of intended use is at the center of the tube around 4–6 inches in depth, the acoustic field within the standing wave tube is acceptable for further use in the characterization of MEMS sensors.

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IV. SENSOR CHARACTERIZATION AND COMPARISON

With the characteristics of the standing wave tube established, it can be evaluated for suitability as a vessel for characterization of acoustic measurements. To determine the standing wave tube's viability as a characterization environment, characterization tests will be performed on the sensors placed within the standing wave tube and the results of these tests will be compared to data taken from similar characterization testing carried out at TRANSDEC.

A. EXPERIMENTAL SETUP

The standing wave tube and corresponding instrumentation, described in Chapter 3, was used to characterize the *Ormia*-inspired-MEMS sensor. The sensors are placed within the standing wave tube using specially designed mounting components. The sensor and circuit board are protected from water by a 3D printed housing shown in Figure 21. The MEMS sensor is powered by an Agilent E3620A Dual Output DC Power Supply and is connected to a PC via a Zurich MFLI for data collection.



Figure 21. Sensor Housing

The sensor housing is designed to connect with a cylindrical 3D printed cage mounted to a continuous rotation stage. The continuous rotation stage allows the sensor to be rotated a full 360 degrees; this enables the sensor's directionality response to be characterized without moving the acoustic source. The continuous rotation stage is controlled by a dial on top a drive shaft connected to the controls of the continuous rotation stage. Figure 22 shows the sensor attached to the rotation mechanism within the standing wave tube.

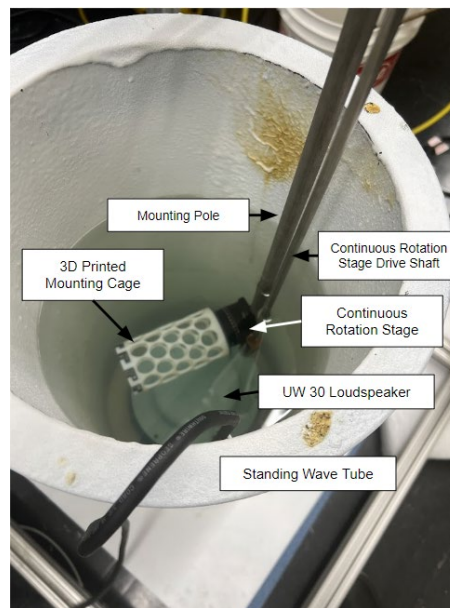


Figure 22. 3D Printed Cage and Continuous Rotation Stage

Another important consideration is the mechanical coupling between the tube and the sensor. Any vibration on the tube would be sensed by the sensor if there is any contact or coupling mechanism, interfering with the measurement. To minimize this effect, a frame constructed of 80/20 Aluminum T-Slotted Bar was constructed around the standing wave tube to serve as a stable mounting point for the sensor rotation assembly. Additionally, the frame was placed on top of four Styrofoam pads to minimize any vibrations that may be transferred through contact with the floor. Figure 23 shows a top-down view of the frame over the SWT.

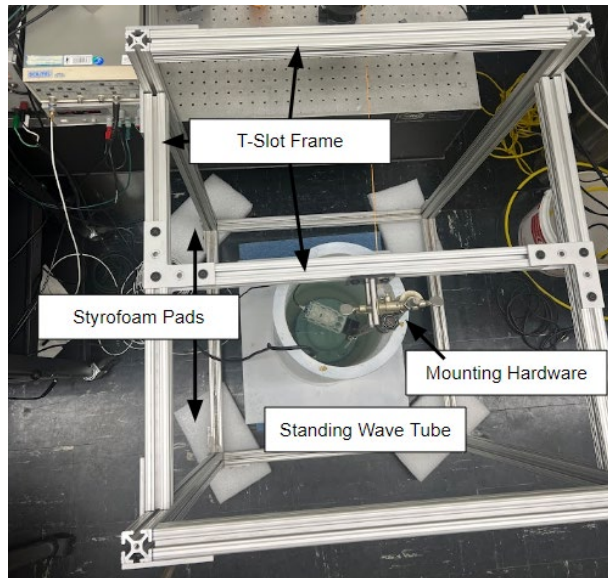


Figure 23. 80/20 T-Slot frame

B. SENSOR CHARACTERIZATION IN THE STANDING WAVE TUBE

To characterize the sensor's performance three tests were performed: a normal incidence DOA frequency sweep, frequency sweeps at 15-degree increments of rotation, and continuous rotation. These three tests investigate the sensor's frequency and directionality response.

1. Normal Incidence DOA Frequency Sweep

The first test conducted on the sensor was a frequency sweep with the sensor directly pointed at the loudspeaker, at normal incidence. The main purpose of this test is to find the resonant frequency of the sensor. As discussed in chapter 1, the MEMS sensors are carefully designed with precise dimensions so that the sensor has a specific resonant frequency. At this frequency, the sensor is expected to demonstrate the largest sensitivity. To measure this, the sensor was placed in the standing wave tube at a depth of approximately 5" and the UW 30 was driven with 0.35 V of power and swept frequencies from 400 Hz to 1000 Hz in 2 Hz increments. In order to calculate the sensor's sensitivity, the same test was performed with a BK 8103 omnidirectional hydrophone. Carrying out this test with a calibrated hydrophone establishes the acoustic pressure that is influencing the sensor's response. The following formula was used to calculate the sensor's sensitivity,

$$S_s = \frac{R_s G S_h}{R_h},$$

where S_s is the calculated sensitivity of the sensor, R is the response measured from the sensor, G is the gain applied to the BK 8103 during testing, S_h is the sensitivity of the BK 8103 hydrophone, and R_h is the response recorded from the BK 8103 hydrophone.

Figure 24 shows the sensor's sensitivity over a 400–1000 Hz frequency range. The frequency response plot shows a smooth, well-defined peak centered over 670 Hz. This is a good initial indicator that the standing wave tube is a suitable environment for sensor characterization as the observed resonant frequency is very near the design value.

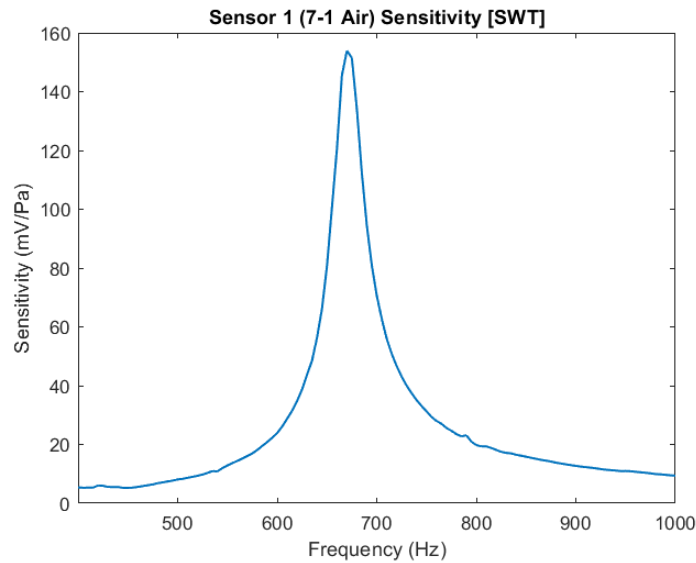


Figure 24. MEMS Sensor Normal Incidence DOA Frequency Sweep (SWT)

2. Frequency Sweeps at 15 Degree Increments

The sensor's DOA response is another quantity that must be characterized. The sensor has a cosine dependence based on the incidence of angle of the sound. This means the sensor is expected to give a maximum response at a DOA of 0 and 180 degrees, with minimum response at 90 and 270 degrees [11]. To characterize the sensor's frequency response, the loudspeaker was swept over a frequency range from 400–1000 Hz in 5 Hz

increments. The sensor was first oriented to be directly pointing at the loudspeaker and after each frequency sweep, the sensor was rotated 15 degrees; this process was repeated until a final measurement was recorded when the back side of the sensor was pointed towards the loudspeaker. Figure 25 shows the sensitivity from 0 to 90 degrees and Figure 26 shows the sensitivity from 90 to 180 degrees.

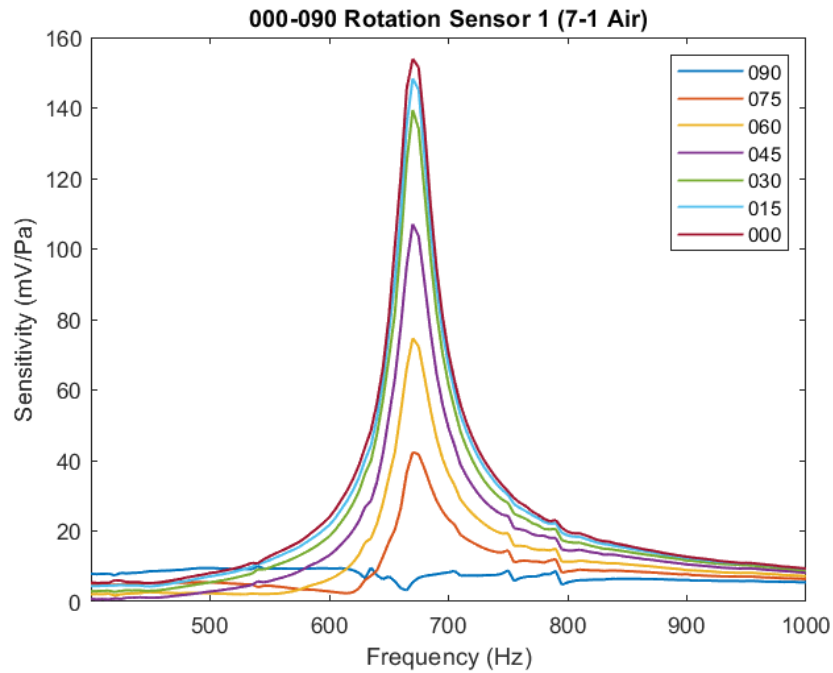


Figure 25. MEMS Sensor Sensitivity from 000-090 DOA

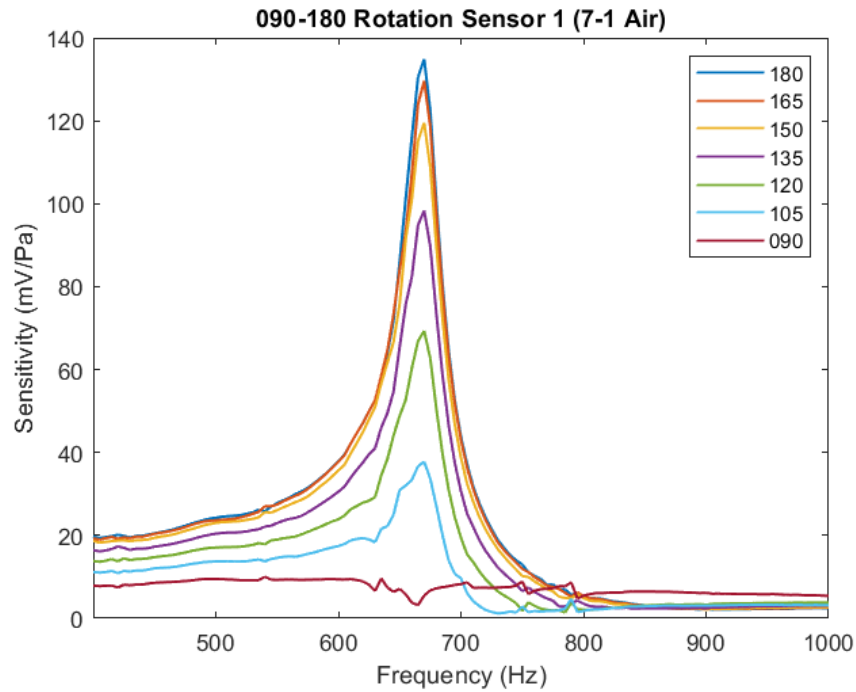


Figure 26. MEMS Sensor Sensitivity from 090–180 DOA

Overall, the sensor demonstrated the expected behavior within the standing wave tube; a minimum response was observed at a DOA of 90 degrees and a relative maximum at 0 and 180 degrees. However, the maxima at 0 and 180 degrees are expected to be equal; instead, the results show that they differ by approximately 12%. While this does not represent ideal behavior, this trend has been regularly observed in previous testing of the same MEMS sensor and it is most likely to be due to the effects of housing and mounting.

3. Continuous Rotation Test

The continuous rotation test involves rotating the MEMS sensor a full 360 degrees at a constant angular velocity while the loudspeaker continuously emits a single frequency. Similar to the frequency taken at 15-degree increments, the purpose of continuous rotation test is to obtain the sensor’s directional response over all angles.

The single frequency chosen was 670 Hz as this was the frequency that demonstrated maximum sensitivity at normal incidence. In order to continuously rotate the sensor within the tube, an Edelkrone HeadOne was used. The Edelkrone HeadOne is a

high-quality stepper motor whose intended use is as a panning device for high-end video cameras. Here, it is employed by affixing it to the T-Slot frame and connecting the drive shaft of the Edelkrone to the turn dial controlling the continuous rotation stage via a belt and pulley system. Figure 27 shows the Edelkrone attached to the T-Slot frame and connected to the rotation mechanism.

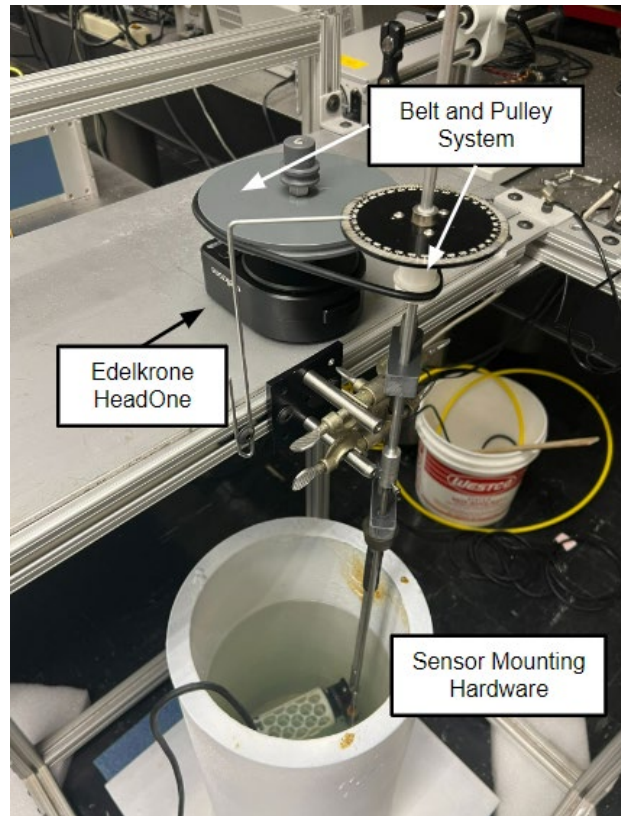


Figure 27. Continuous Rotation Experimental Setup

Once the Edelkrone is properly connected to the continuous rotation stage, the Edelkrone is provided the input signal to begin continuous rotation. Once it begins rotating, the MEMS sensor's response is recorded for one entire rotation. Figure 28 shows the sensitivity of the MEMS sensor over a 360-degree continuous rotation and Figure 29 is a polar plot representation of the same data.

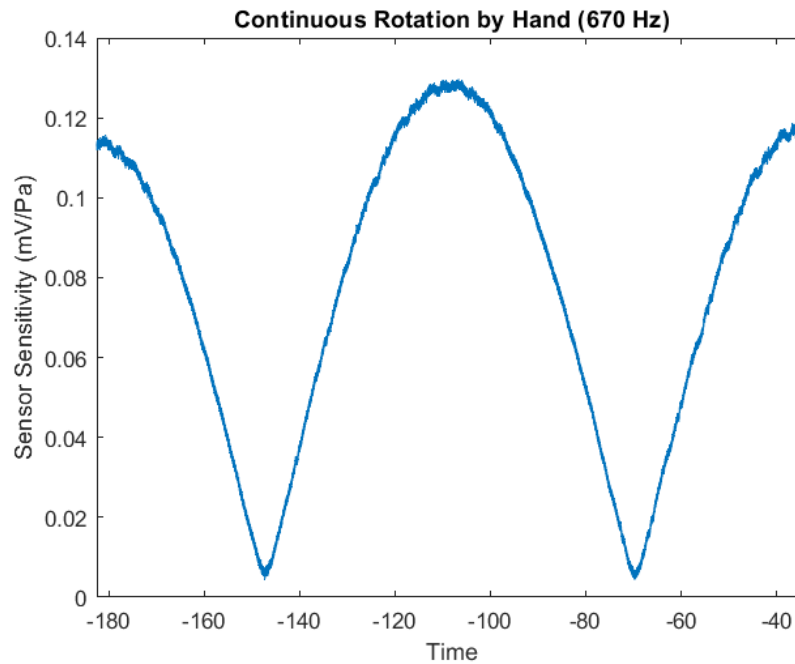


Figure 28. Continuous Rotation of MEMS Sensor with Edelkrone HeadOne

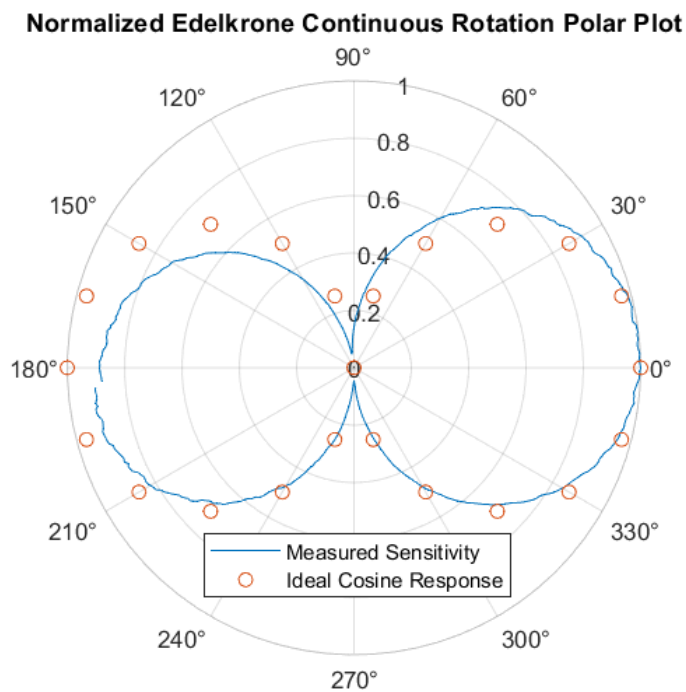


Figure 29. Polar Plot of Continuous Rotation of MEMS Sensor with Edelkrone

The overall shape of the continuous rotation plot does follow the ideal cosine behavior that is expected of the sensor. There is a clear difference in lobe size between the front and back of the sensor. This behavior is not ideal, but it does follow trends observed in previous measurements of the same sensor.

C. COMPARISON WITH DATA OBTAINED IN TRANSDEC

In order to determine the effectiveness of the standing wave tube as an environment for the characterization of acoustic sensors, the data recorded from a MEMS sensor in the standing wave tube is compared to data recorded from the same MEMS sensor while it was in the anechoic pool at the Transducer Evaluation Center in San Diego, CA in December of 2022. The 6 million gallon, elliptically shaped freshwater pool, is 91 meters long, 61 meters wide, and 12 meters deep and is designed to minimize ambient sound and acoustic reflections, making it an ideal testing environment for acoustic sensors [13]. Figure 30 is a photograph of the TRANSDEC anechoic pool.



Figure 30. TRANSDEC Anechoic Pool. Source: [27].

1. Normal Incidence DOA Frequency Sweep

At TRANSDEC the experimental setup for all tests was the same. To hold the sensor in a fixed location, it was attached to the end of a motorized metal pole at a depth of 6 meters. A BK 8103 was also attached to the pole and placed as close to the sensor as possible. The acoustic source was placed 2 meters away from the sensor, also at a depth of

6 meters. The TRANSDEC Normal Incidence DOA frequency sweep was also carried out over a frequency range of 400 – 1000 Hz in 2 Hz increments while the MEMS sensor was pointed directly at the acoustic source. The sensor's sensitivity was calculated in the same manner as in the SWT tests. Figure 31 shows how the sensor's sensitivity varied with frequency when tested at TRANSDEC.

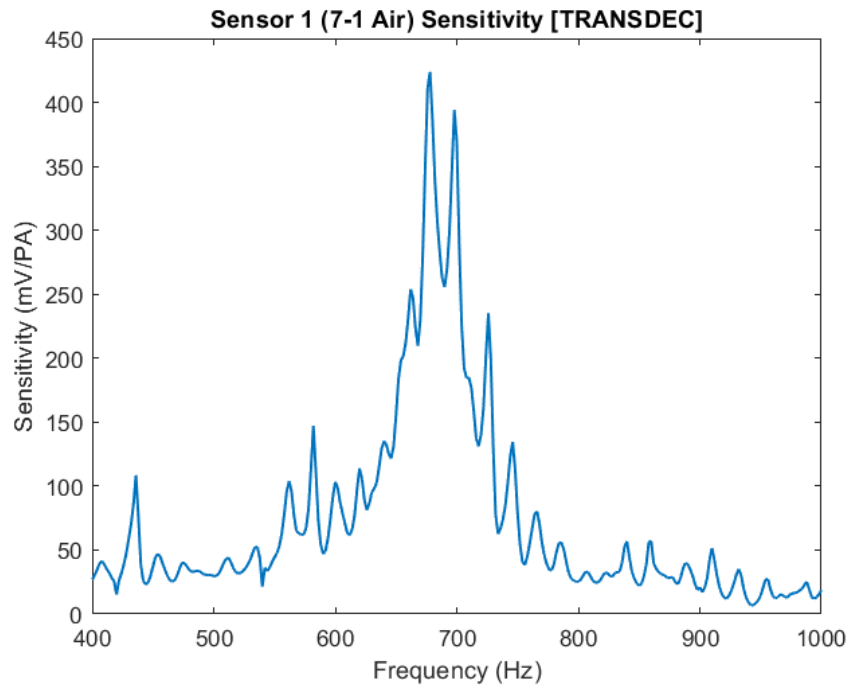


Figure 31. Normal Incidence DOA Frequency Sweep (TRANSDEC)

The TRANSDEC data shows a main peak also around 670 Hz, but overall, the peak is very jagged over the entire frequency range. The fringes in the response are due to the interference pattern caused by the reflections on the water's surface. This can be reduced by using a pulsed stimulus and a gated detection algorithm. Figure 32 shows the normalized sensitivity of the normal incidence frequency sweep in the standing wave tube and at TRANSDEC simultaneously. It is very noticeable that the frequency response curve measured within the SWT is smoother with one well defined peak centered over the intended resonant frequency of 670 Hz. The standing wave characteristic of the tube mitigate the problem with surface reflections encountered at TRANSDEC.

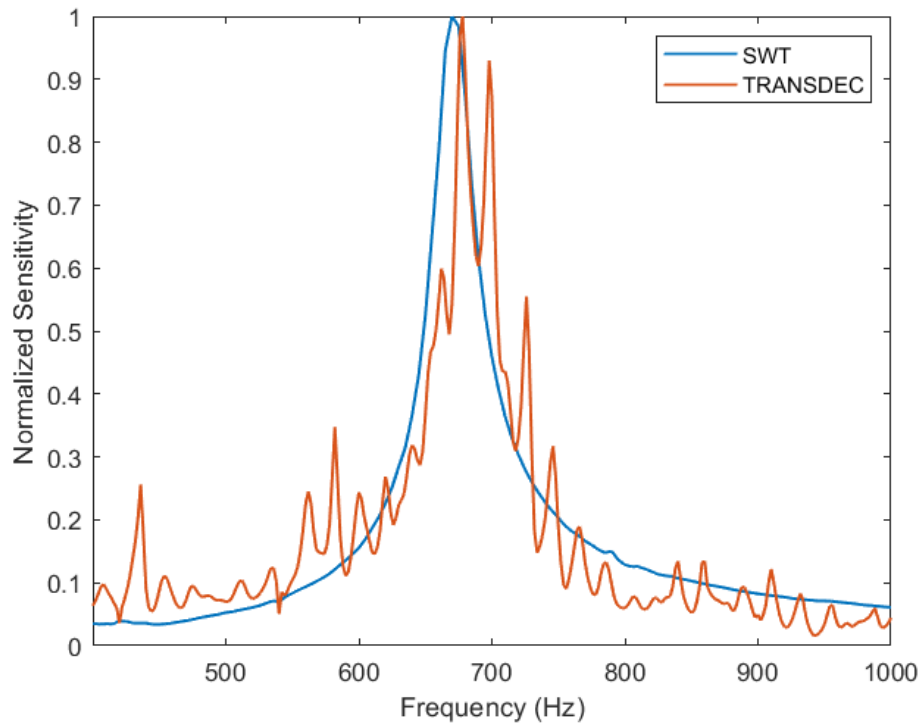


Figure 32. Normalized TRANSDEC and SWT Sensitivities

2. Continuous Rotation Test

The methodology of the continuous rotation test performed at TRANSDEC was identical to what was performed in the standing wave tube. However, for continuous rotation the metal mounting pole used at TRANSDEC is directly connected to a DC motor. Figure 33 shows the normalized sensitivity measured during the continuous rotation performed with the in the standing wave tube plotted simultaneously with the continuous rotation data from TRANSDEC.

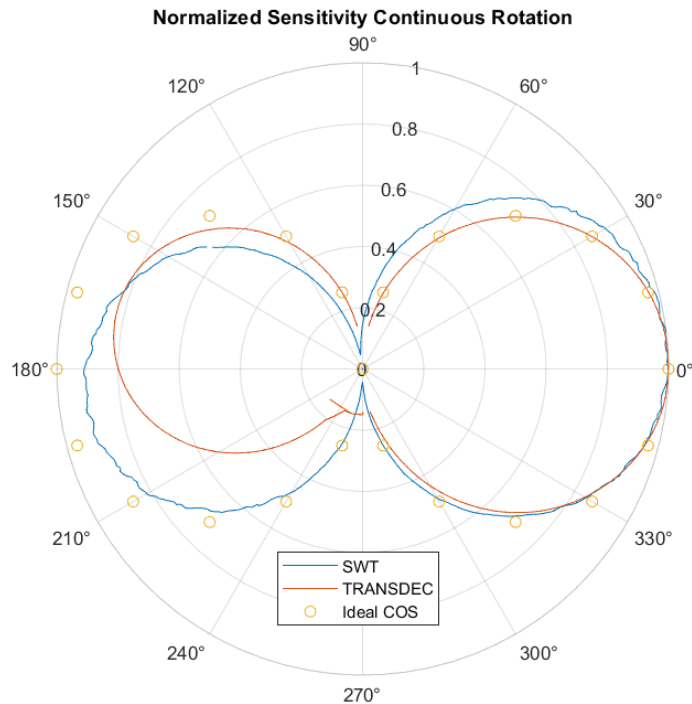


Figure 33. Comparison of Continuous Rotation with Normalized Sensitivity

The two curves both show the same lobe size difference between the front and back sides of the sensor. However, there is a noticeable difference between the standing wave tube and TRANSDEC measurements themselves. This difference is likely due to differences in mounting and housing between the two-testing setups. Despite these differences, the measurements recorded in the standing wave tube are similar to what was measured at TRANSDEC, indicating that the standing wave tube set up is a comparable replacement for characterization of these acoustic MEMS sensors.

V. CONCLUSION

The main goal of this research was to characterize the acoustic field of a standing wave tube to determine its viability as an environment for the characterization of direction-finding MEMS sensors in an underwater environment. The motivation for the development of the Sensor Research Lab standing wave tube is that previously used environments have either proved unsuitable for sensor characterization or logistically intensive to use. Current tanks at NPS produce a high amount of acoustic reflections, creating complex acoustic fields that stimulate the sensor from many angles simultaneously making it impossible to assess the directionality response of the sensor. The anechoic pool at TRANSDEC has produced great results but is hundreds of miles away and requires booking months in advance. These factors created the need for a suitable in-house characterization environment, the standing wave tube.

A. IMPLICATION OF RESULTS

The standing wave tube exploits the homogenous nature of waves with flat wavefronts to create a stable acoustic environment that can be used for sensor characterization. This research used COMSOL finite element analysis software to establish a baseline of expected behavior and show that, in principle, the standing wave tube will produce a suitable acoustic field. The model was verified through characterization of the standing wave tube in the laboratory. Characterization measurements demonstrated that there is region of flat wavefront propagation within the standing wave tube that extends from the water's surface to approximately 6 inches in depth. This region of flat wavefront propagation means the standing wave tube can be used as characterization environment for direction-finding acoustic MEMS sensors.

To evaluate the quality of the standing wave tube as a characterization environment, a sensor previously characterized at TRANSDEC was characterized in the standing wave tube. Overall, standing wave tube performed well when comparing sensor data measured in the standing wave tube and TRANSDEC data. In the standing wave tube a smoother frequency response curve was measured. TRANSDEC data had many jagged features that

were the result of an interference pattern caused by reflections off the water's surface. In the continuous rotation measurements, both the TRANSDEC and SWT results followed a general cosine dependence. However, both showed a difference in lobe size between the front and back side of the sensor. This, along with the difference in lobe size between the two measurements, is acceptable as it has been regularly observed in previous characterization measurements and is suspected to be caused by the housing and mounting hardware used in the experimental setup.

The ability for the 6 gallons of water in the standing wave tube to achieve comparable results to the 6-million-gallon TRANSDEC anechoic pool presents a huge benefit to the Sensor Research Lab. The standing wave tube allows for sensors to be iterated and improved upon much more rapidly. A quality in-house characterization environment means it no longer takes months of planning and thousands of dollars to characterize sensors.

B. SUGGESTIONS FOR FUTURE WORK

The overall shape and trends demonstrated by this MEMS sensor in the standing wave tube match the overall expectations of sensor performance. However, the differences in specific values should be investigated further. This can be accomplished by characterizing other MEMS sensors in the standing wave tube that were also previously characterized at TRANSDEC. This will help determine if the discrepancy is specific to this sensor configuration or is being caused by an element of the standing wave tube setup.

The continuous rotation setup using the Edelkrone Headone is a good option that produces suitable results, but it can be further optimized. The housing and mounting hardware involved in this setup is suspected to be the cause of the differences in sensor response data; therefore, the housing and mounting setup should be simplified as much as possible. The first step should be removing the continuous rotation stage and replacing it with a pulled directly mounted to the 3D printed cage. This change would remove a component of the set up that has many moving parts that are potential sources of vibration that negatively influence sensor characterization.

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